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COMBUSTION OF FUEL DROPS. FORCED CONVECTION AND INTERACTION EFFECTS

by

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and

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Madrid, 20 September 1956
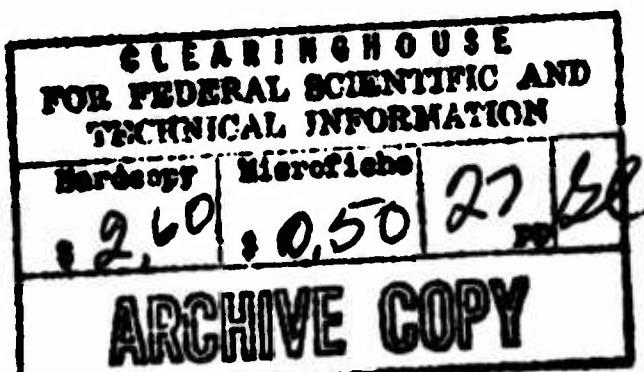
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- SUMMARY -

1.- A brief review is made of the theoretical and experimental
results in reference with the combustion of single fuel drops
in a still atmosphere.

2.- Several experimental results on the effects of forced
convection and interaction in the combustion of fuel drops
are given and compared to those for the case of a single
drop in a still atmosphere. These results were obtained at
the Combustion Laboratory of the INTA (*).

3.- Analysis is made of the possible application of this
experimental evidence to the combustion of sprays.

1.- <u>Introduction</u>: The development of the new jet propulsion systems has promoted the study of some dynamic aspects of combustion which were considered of secondary importance in the classical propulsion systems.

In a jet engine the size of the combustion chamber is determined by the limitations impossed to the velocity of the gases through it. Such limitations arise from the phenomena of flame stabilization, shock conditions and by the minimum residence time of the fuel in the chamber required to obtain a satisfactory combustion efficiency. The study of combustion in one of these chambers is a difficult task due to the great number of variables that deal in the process and to the fact that the over-all process results from the coexistance and interaction of several phenomena of different nature. This is specially true when, as it normally occours, the fuel is introduced in the burner in the liquid state. In such case, combust: should be preceded by the atomizing of the fuel jet, the fractioning and dispersion of the drops, fuel evaporation and its mixing with the oxygen. Then, combustion can tak place in the following ways: a) Laminar or turbulent flam propagation through a mixture of fuel vapors and oxygen. b) Quasi-homogeneous combustion of the mixture. c) Flame propagation through a fuel mist in an oxidizing atmosphere. d) Combustion of drops or of systems of drops with individu or common flames. The relative importance of these phenome depends in each cas on the characteristics of the combustio chamber.

One of the following methods can be used to study combustion processes in a burner: a) By deducing empirical rules from.

designing experience. b) By testing models and applying the similitude laws. c) By thoroughly investigating the laws governing the actual phenomena.

A preliminar phase of such an investigation is the separate study of each one of the elementary phenomena which influence the process. The present paper is a contribution along this line. It contains a study of the combustion of drops considering the effects of forced convection and of the interaction due to the vicinity of other drops. Results should be a starting point for the analysis of a more complex but practical problem - the combustion of sprays - .

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2.- <u>Combustion of an isoleted drop in air at rest</u>.- Several studies were performed during the last years - both theoretical and experimental-on the combustion of a fuel drop in an oxidizing atmosphere at rest [1 to 3] .

Figure 1 summarizes the process. A flame forms surrounding the drop and it stretches upwards due to free convection. The drop acts as a fuel source receiving from the flame the heat needed for evaporation. Fuel vapors diffuse from the drop towards the flame where they mix with the in-coming oxygen and burn. Automatically a balance establishes wich controls the amount of fuel burnt per unit time and, therefore, the burning rate of the drop.

The fundamental result of such studies can be summarized in the following formula, which gives the law of variation of

the size of the drop as a function of burning time :

$$r^2 = r_o^2 - kt \qquad\qquad (1)$$

Here, r is the drop's radius, r_o is the initial radius, t the time measured from the moment at which combustion starts and k is an "evaporation constant" depending on the physico-chemical characteristics of the fuel and on the composition and state of the surrounding atmosphere. Formula (1) also holds when the drop evaporates without combustion. In such case the value for the evaporation constant changes.

Figure 2 shows the theoretical values of the evaporation constant of a Benzene drop vaporizing in air, with and without combustion, as a function of the atmosphere's temperature (*).

As an example, Figure 3 shows some experimental curves on the time variation of the square of the drop radius obtained at the INTA Combustion Laboratory. The same figure also shows the experimental and theoretical values of their respective evaporation constants. Experimental values were obtained through the conventional technique consisting in suspending drops from a thin quartz filament and recording photographically the time variation of their mean diameter.

Very small drops (with radius of the order of 5 μ) cannot stabilize a diffusion flame of the type shown in figure 1 . With very small drops, fuel cloud burn with flames of characteristics very similar to those of premixed flames [4] .

(*).- Influence of pressure is very small. Influence of dissociation has been neglected .

3.- <u>Influence of Convection</u>.- The experimental results referred
to herein were obtained under the influence of the free
convection arising from the heating of the gases. On the
other hand, theoretical results refer to an ideal case where
free convection is non-existent. This gives a spherical
symmetry to the phenomenon enabling its theoretical analysis.
Comparison of these results suggests that the influence of
free convection is not too important. However, the problem
cannot be considered as solved as long as there is not enough
experimental evidence without convection, such as that
obtained by Kumagai in Japan [5].

Since fuel drops move in a burner through air it is important
to know the influence of forced convection on combustion. A
theoretical study of such problem is very difficult and has
not been performed to date. On the other hand, experimental
studies have been carried out by observing the combustion of
fuel drops within an air stream. Frequently, in such experi-
ments fuel drops were substituted by porose spheres to which
fuel is supplied and from its consumption the burning rate
of the equivalent drop could be controlled. In the experimens
performed at the INTA fuel drops were suspended from a quartz
filament [6]. A drawing of the installations is shown in
Fig. 4. The following combustibles were tested : Benzene,
Toluene, n-Heptane, Ethyl-Alcohol and Methyl-Alcohol. Ex-
perimentation was mainly carried out at laboratory conditions
(T ≈ 20ºC) but some results were obtained with air heated up
to a temperature of 80ºC. The Reynolds Numbers of these
experiments ranged from 0 to 60, where very few experimen-
tal results are available. The maximum Reynolds Number that
could be reached in such experiments was determined by the

extinction velocity of the flame (see Paragraph 6) .
Results show that the fundamental effects of forced convec-
tion are as follows : a) It activates normal combustion (*)
increasing the evaporation constant, b) In some cases forced
convection blows-out the front part of the flame and combus-
tion takes place only in the wake of the drop. c) If
velocity exceeds a certain value the flame cannot be
stabilized and it blows-out. Evaporation of the drop
proceeds without combustion.

4.-   Types of Flames.- In the combustion of Benzene, Toluene and
n-Heptane two types of flames were observed: the surrpunding
flame, which will be called normal, similar to that observed
in combustion in a still atmosphere, and the wake flame which
forms in the wake of the drop. The former is a diffusion
flame and the latter a premixed flame. With Ethyl-Alcohol
and Methyl-Alcohol, wake combustion could not be observed
under the conditions of our experiments.
With low blowing velocities, normal combustion is the stable
one. With high velocities only wake combustion is possible.
When working at ambient temperature there is a large tran-
sition zone where either type of combustion can take place.
depending on the location of the ignition point. When the
air temperature is increased the transition zone disap-
pears and wake combustion becomes more stable.
The transition from one type of flame to the other, during
combustion, is characterized by the extinction of the flame
at the forward stagnation point of the drop when velocity

(*). That is to say when the flame surrounds the drop.

reaches a certain value, after which, the flame should
stabilize in the wake of the drop. However, under ambient
temperature the spontaneous transition from normal to wake
combustion could hardly ever be observed while it normally
took place when working with hot air.

According to Spalding [3], the extinction of the normal
flame at the forward stagnation point of the drop occurs
for constant values of the ratio "velocity of the air/drop
diameter". It could be verified that this law holds ap-
proximately. This question will be considered in Paragraph
6.

5.- Influence of Forced Convection on the Burning Rate: When
the flame surrounds the drop, convection increases its
burning rate. Let m be the mass of fuel burnt per unit
time under the influence of convection, and m_0 the mass
that would burn under similar circumstances without convec-
tion. Convection effect is measured by the ratio m/m_0.
The problem lies in determining the value for this ratio
and how it depends on the conditions of the phenomenon.
For the case of pure evaporation, without combustion, Fröss-
ling [7] proposed the following semi-empirical formula :

$$\frac{m}{m_0} = 1 + 0.3 \ S_c^{1/3} \ R_e^{1/2} \tag{2}$$

Here, $S_c = \dfrac{\mu}{\rho D}$ and $R_e = \dfrac{2r\rho V}{\mu}$ are, respectively, the

Schmidt and Reynolds Numbers for the phenomenon; ρ and μ
are the density and the viscosity coefficient of the
surrounding atmosphere. D is the diffusion coefficient

between fuel vapors and air, and V is the velocity of
the air stream.

A simple calculation shows that formula (2) can be written
in the form :

$$\frac{dr^2}{dt} = - k_o(1 + 0.3\, S_c^{1/3}\, R_e^{1/2})$$ (3)

where k_o is the evaporation constant without convection.
Equation (3) enables the definition of an instantaneous
evaporation constant k :

$$k = - \frac{dr^2}{dt}$$ (4)

which, by virtue of (3), is given by :

$$k = k_o (1 + 0.3\, S_c^{1/3}\, R_e^{1/2})$$ (5)

Since k depends on r through R_e , formula (4) shows
that for the case of evaporation without convection the
linear law (1) does not hold.

It has been suggested that the Frössling Law (5) also holds
for the combustion case, provided that in the expression of
Reynolds Number, ρ and μ are referred to a temperature
ranging between ambient and flame temperatures.

The scarce experimental evidence available [3] , [8] suggests
the validity of this assumption. The Reynolds Numbers of
the measurements performed at the INTA were not large
enough to clarify this matter. Figure 5 shows the law of
variation of r^2 as a function of time, for different
values of blowing velocity V for Benzene. When the
values of R_e are small, which was the case in such

experiments, the solution of (4) is almost a straight line with a slop (- k_1) where k_1 is the value for k corresponding to the drop's initial radius in Eq. (5). This is shown in Fig. 6 ,which represents different solutions of Eq. (4) corresponding to several values of parameter :

$$\alpha = \frac{k_1}{k_0} - 1 . \qquad (6)$$

This explains why the lines in Fig. 5 are substantially straight .

Fig. 7 gives the variation of k_1 as a function of V for five different combustibles. Each point on these curves represents a mean value of several experiments. The initial part of the curves up to the inflection point corresponds to the zone in which the influence of free convection prevails. If free convection were absent, the curves would
continue by a dashed line as shown for the case of Benzene. The evaporation constant corresponding to wake combustion is considerably smaller and it decreases very rapidly as blowing velocity is increased. This is shown in Figs. 8 and 9 which give the experimental results for Benzene and Toluene respectively.

At present not enough experimental evidence is available on the influence of ambient temperature in these phenomena.

6.- Extinction and Ignition Phenomena: When the air stream velocity exceeds a certain value the flame extinguishes or cannot be ignited. Spalding [3] deduces theoretically that the extinction of a normal flame occurs when ratio V/d between blowing velocity and drop diameter reaches a certain value, which depends only on the physico-chemical conditions

of the process but is independent from the size of the drop. Figure 10 shows some of the experimental results obtained at the INTA with Ethyl and Methyl Alcohols. Therein it is verified that Spalding's rule tends to hold for large drops even when the measured values for V/d are considerably larger than those predicted by him. Results corresponding to small drops might be masked by the influence of the filament.

Experiments were made at temperatures far lower than those actually existing in a combustion chamber. Not enough information is available on the influence of the atmosphere's temperature on the value of ratio V/d for extinction. However, provided that such ratio does not increase considerably with temperature, drops can only maintain flames for very small velocities. For instance, by assuming for ratio $(V/d)_{ext.}$ a value of 10^3 sec., a drop with a diameter of 50μ could only maintain a flame when its velocity with respect to the surrounding atmosphere were smaller than 5 cm/sec. This value is very small when compared to the inlet velocity of the drop in a combustion chamber, which is normally of several meters. Therefore it is concluded that the drop will evaporate without combustion in the major part of its path. However, at very high temperatures it should be taken into consideration that the difference between evaporation constants with and without combustion tends to reduce (as shown in Fig. 2). Due to this, the absence of the flame does not increase too much the evaporation time of the drop as would happen under ambient conditions.

With respect to ignition it was verified that it cannot be produced once the flame is extinguished. For ignition the values for V/d are, so far, not available. However the

experiments performed at the INTA show that the minimum ignition diameter incr4ases very rapidly with blowing velocity.

7.- <u>Interaction Effects</u>.- Another aspect of the combustion of drops which should be analyzed as a preliminary phase for the study of the combustion of sprays is the influence of their vicinity on the combustion of each drop.
Rex, Fuhs and Penner [9] have performed some experimental studies on this matter at the California Institute of Technology by suspending two or more drops from quartz filaments. Similar experiments were done at the INTA by burning two side-by-side drops and one drop within the wake of another. Also one drop was burnt in the diffusion flame formed on the free surface of a fuel, equal to that of the drop [10] .
Results obtained show that, in general, interaction effects are weak and that law (1) for isolated drops holds in all studied cases. This is shown, for example, in Fig. 11 .
The scattering of results and the difficulty to obtain mean values, since it is hardly possible to reproduce identical geometrical conditions, added to the weakness of the effects, prevent giving quantitive laws for the variation of the evaporation constant.
Figure 12 gives, as a summary of results, the mean values for the evaporation constants in the case of two side-by-side drops, as a function of the distance between their centers. Each point represents the mean value of the measured constants for a set of experiments (a minimum of ten). It is seen that interaction effects can only be appreciated when

the distance between drop centers is smaller than 5 mm. The shape of the curve seems to have a maximum but the existence of this maximum is not too clear. Figure 12 also includes some results that correspond to the case of two drops one within the wake of the other. In this case scattering is larger due to the oscillations of the flame surrounding the drop under measurement.

In order to analyze stronger interaction effects the evaporation and combustion of a drop inside a diffusion flame formed on the free surface of a fuel was also studied. In this case law (1) also holds but the evaporation constant showed a 50 percent reduction when the drop was placed in the center of the flame where it evaporated without combustion due to the lack of oxygen. This constant increased as the drop approached the reaction zone due, obviously, to the increasment in temperature of the gases surrounding the drop.

8.- Combustion of sprays.- The preceding results suggest the possibility of a study on the combustion of sprays starting from the combustion of isolated drops by assigning an evaporation constant to the spray under the assumption that law (1) holds for each one of its drops.

By knowing the size distribution of drops the preceding assumption enables the computation of the characteristics of the combustion of a spray. Namely the amount of fuel existing at all times in the burner, the size distribution in it, etc. Probert [11] has performed a theoretical study of this kind through an analysis of the influence of the size distribution on the combustion of sprays. Similar studies have been made at the INTA. The available experimental information is scarce

and not conclusive. The INTA is now initiating an experimental program on the combustion of sprays in order to establish the validity of the above mentioned theoretical approach.

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Instituto Nacional de Técnica Aeronáutica

Madrid, September 1956.

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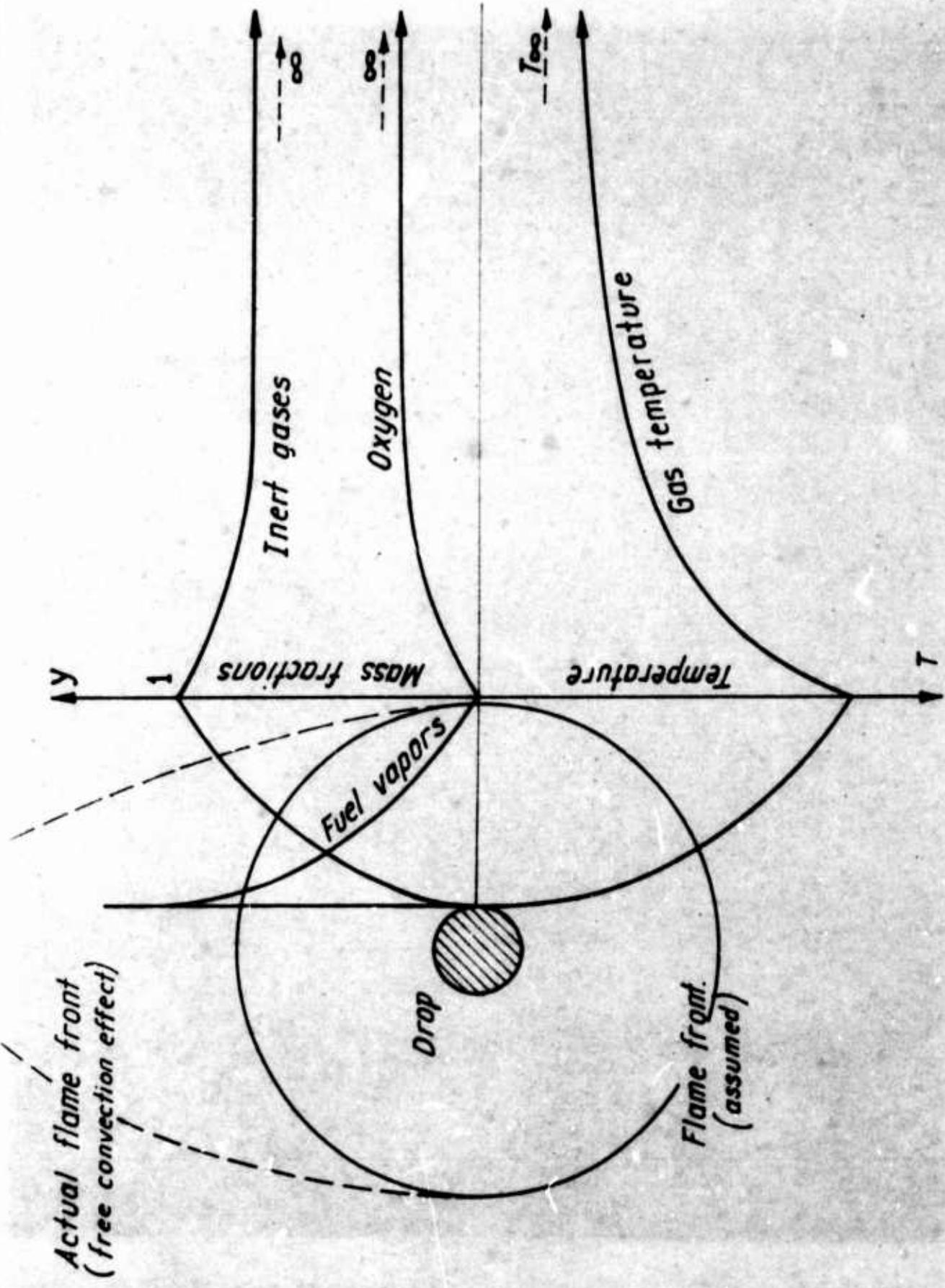
Fig. No. 1 – Combustion of an isolated drop in still atmosphere.
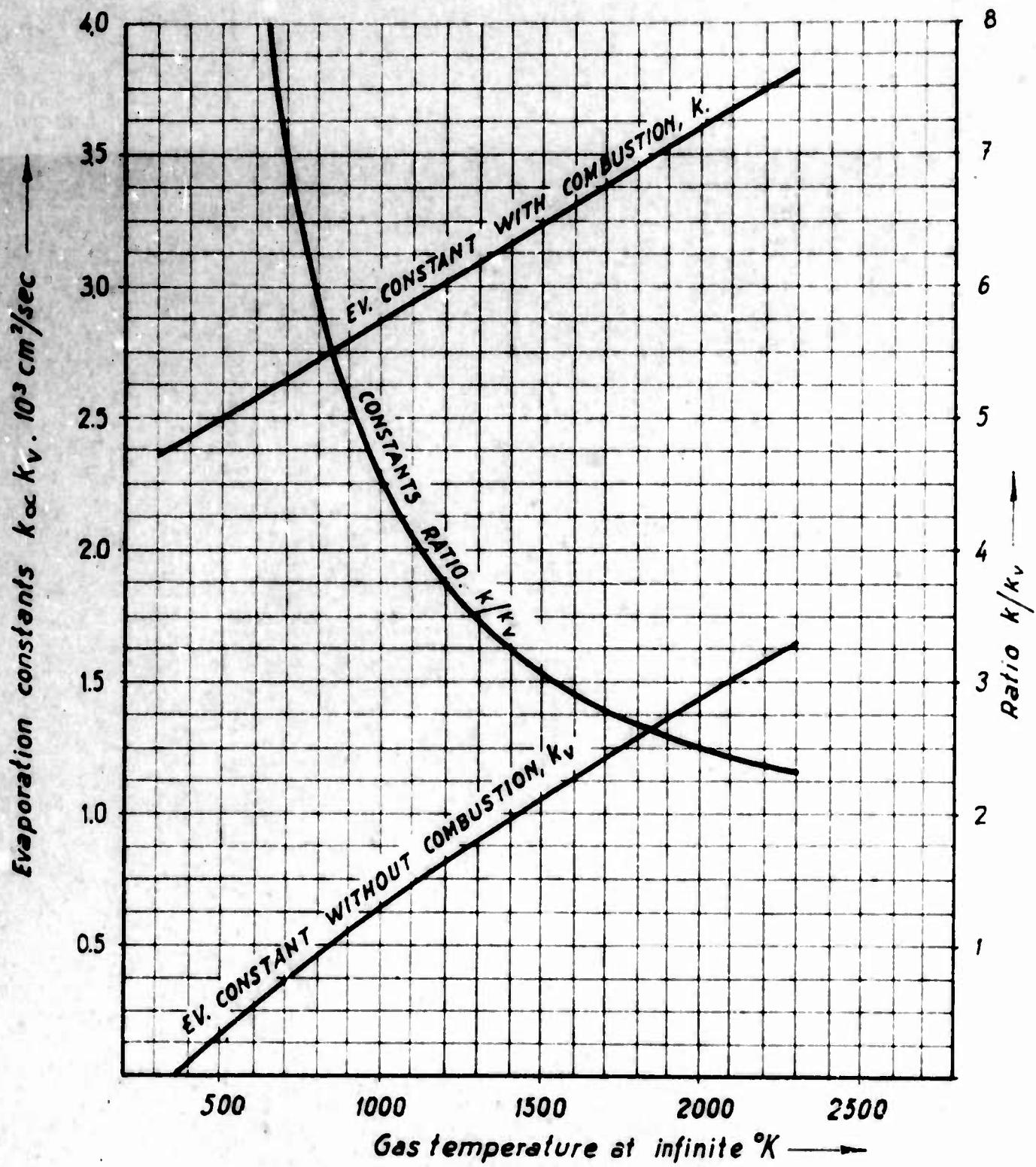
Fig. No 2 - Theoretical variations of the evaporation
constants of a benzene drop as a function
of gas temperature at infinite.
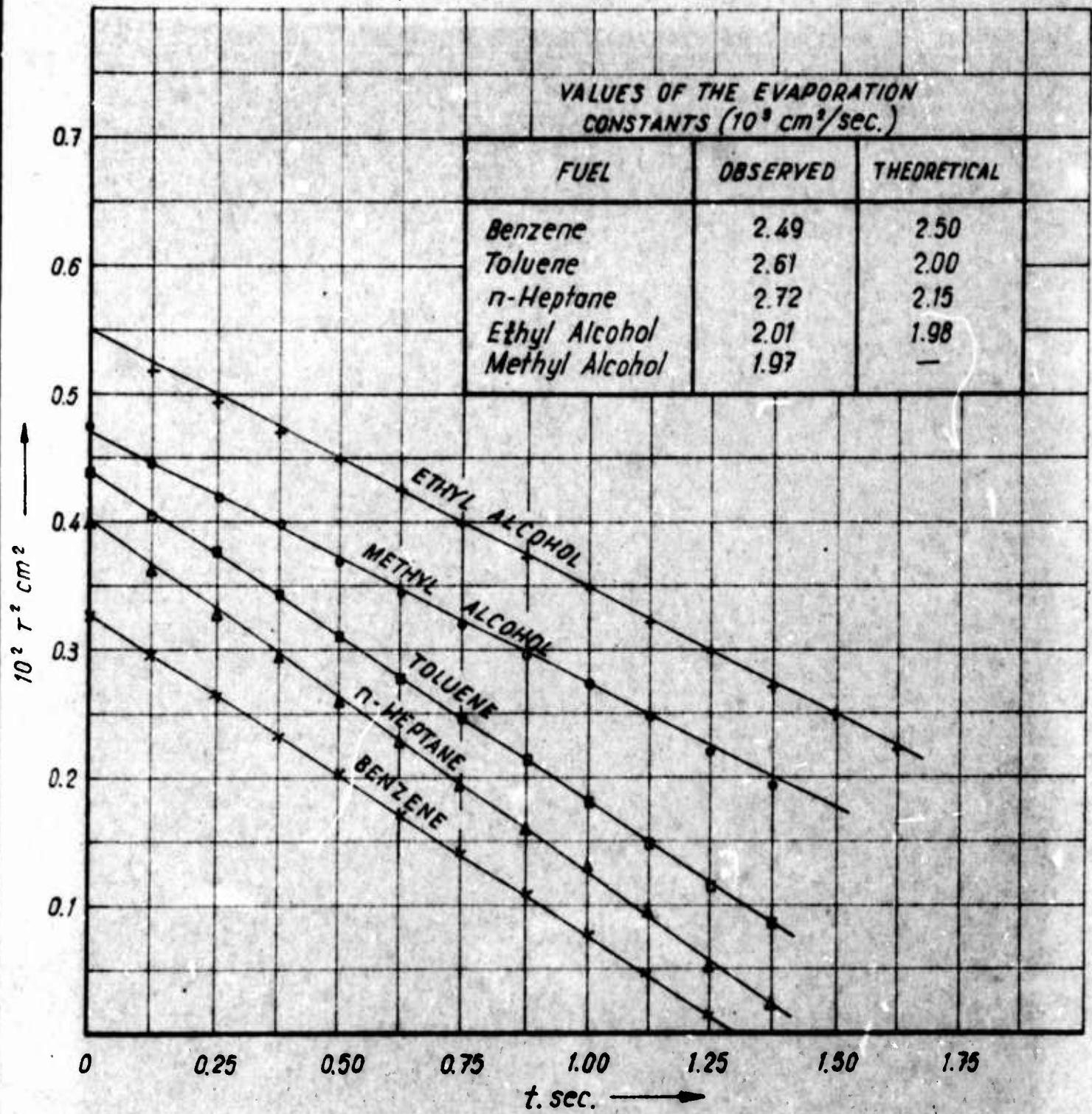
Fig. No3 – COMBUSTION OF ISOLATED DROPS IN STILL ATMOSPHERE (T≈20°C)

Fig. No 4

SKETCH OF THE INSTALLATION
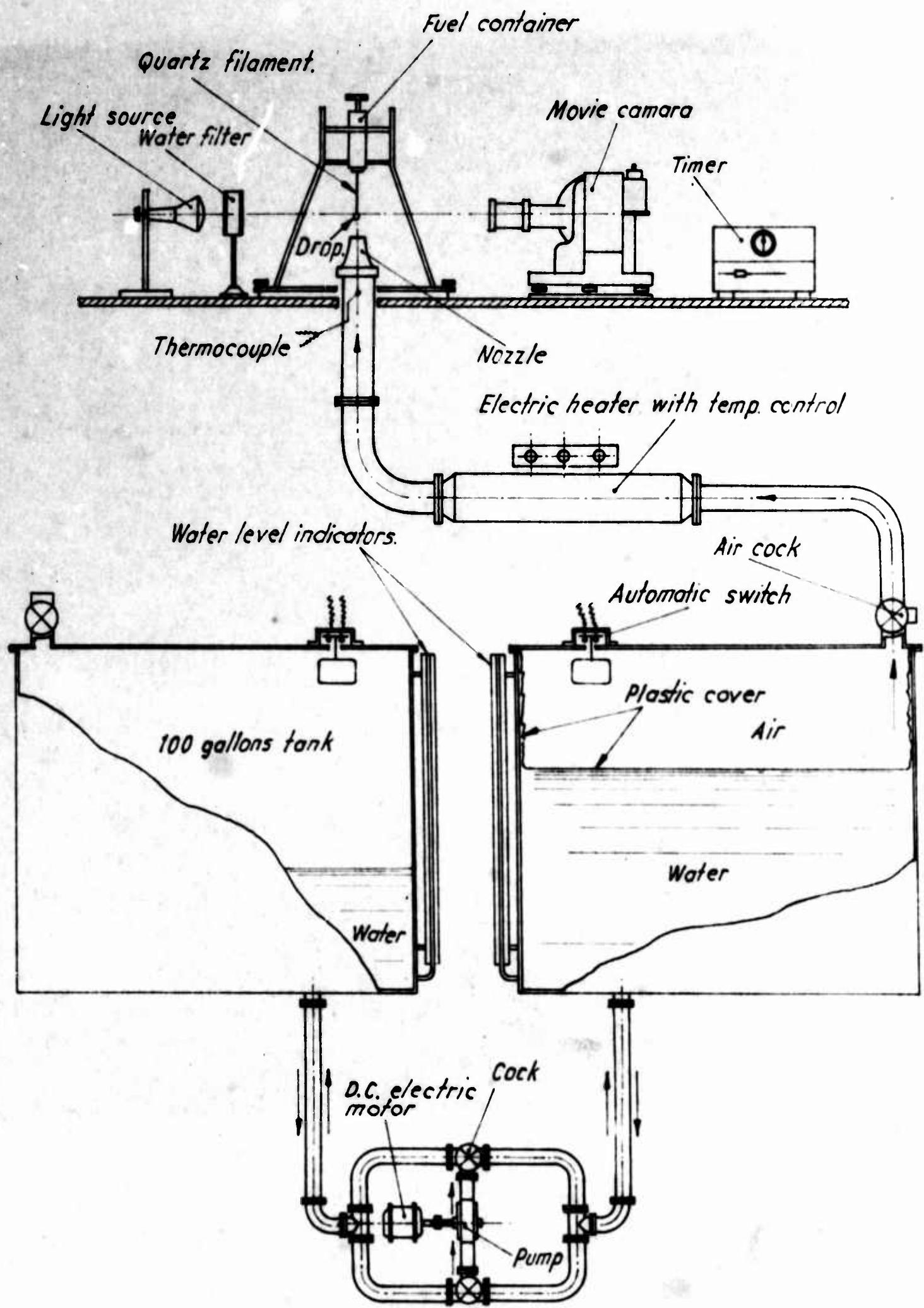
BENZENE

FORCED CONVECTION

Normal Combustion.
$(T \approx 20°C)$

V - cm/sec

k - 10^3 cm²/sec.

$V = 0$ $k = 2.49$

$V = 10.2$ $k = 2.52$

$V = 20.0$ $k = 2.57$

$V = 30.2$ $k = 2.69$

$V = 40.4$ $k = 2.83$

$V = 47.0$ $k = 2.98$

$10^2 r^2$ cm² (arbitrary origin)

t sec.
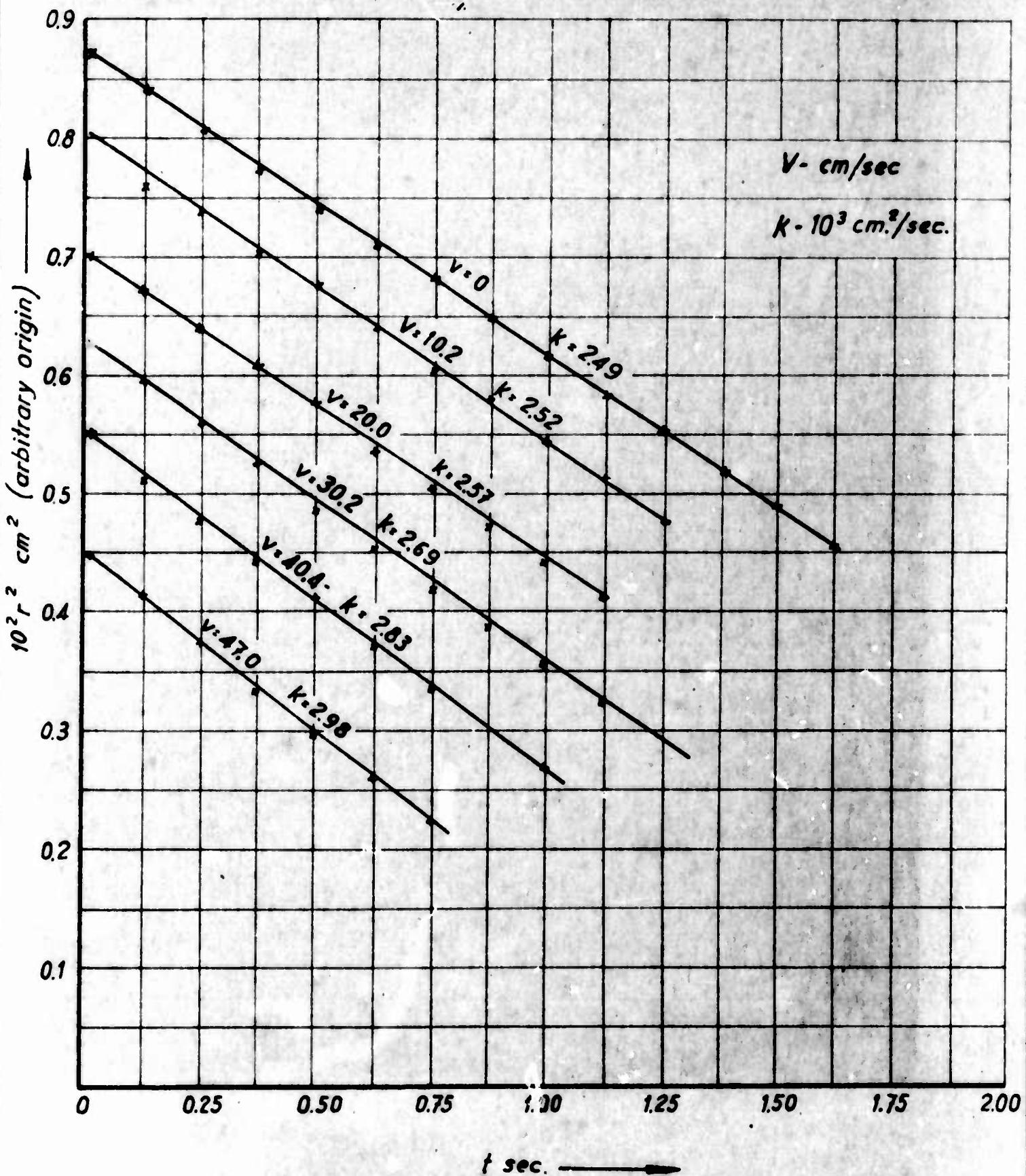
Fig. No. 5 - Time variation of square radius for several blowing velocities.

Fig No 6. Drop radius (dimensionless) as a function of time given by Frössling's formula

Axis label (vertical): $\left(\dfrac{r}{r_o}\right)^2 \longrightarrow$

Axis label (horizontal): $\dfrac{t}{t_t} \longrightarrow$

Curve labels:
$\left(\dfrac{r}{r_o}\right)^2 = 1 - \dfrac{t}{t_c}$ (No convection)

$\alpha = .15$

$\alpha = .30$

$\alpha = .45$

$\alpha = .60$
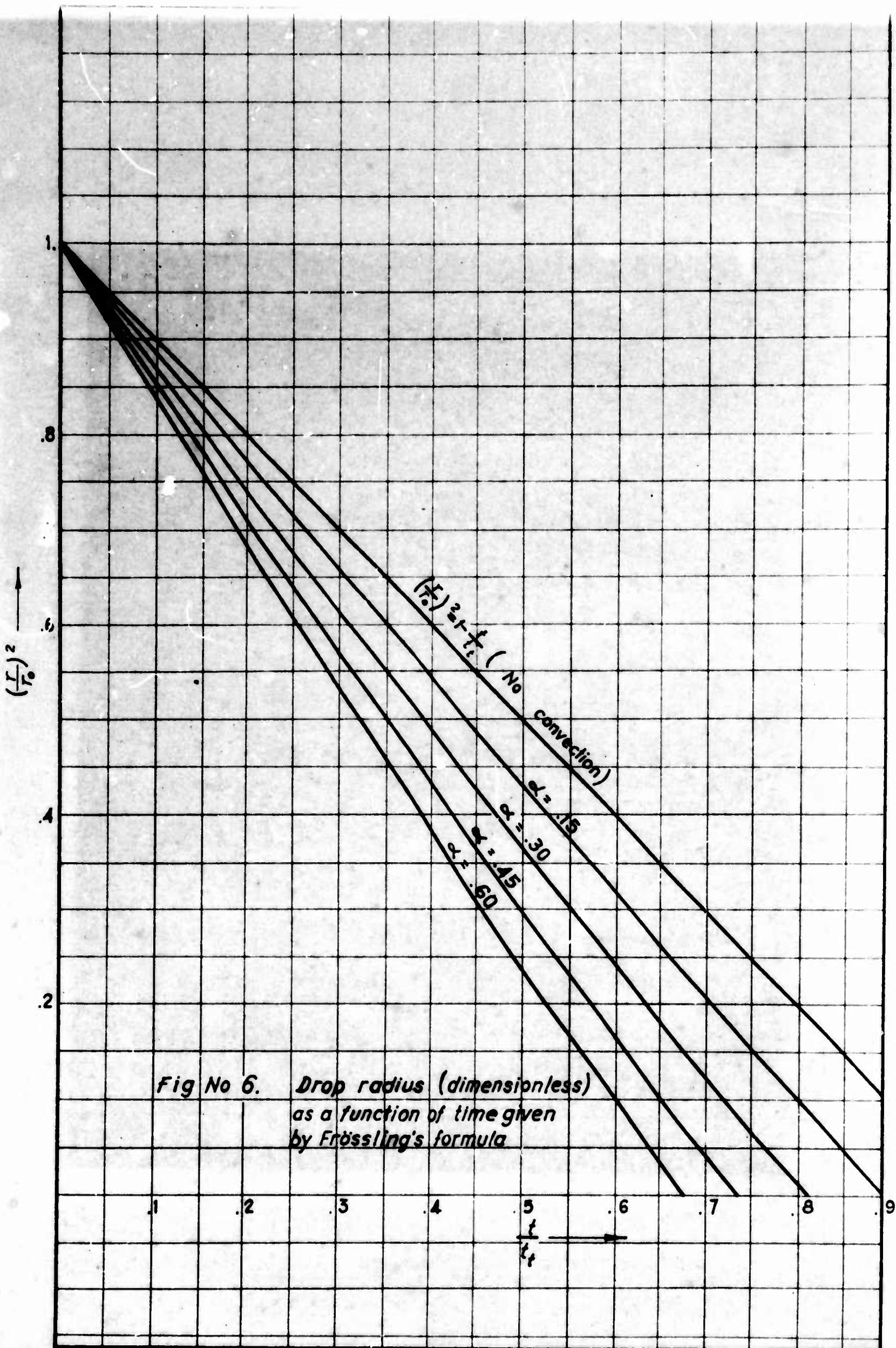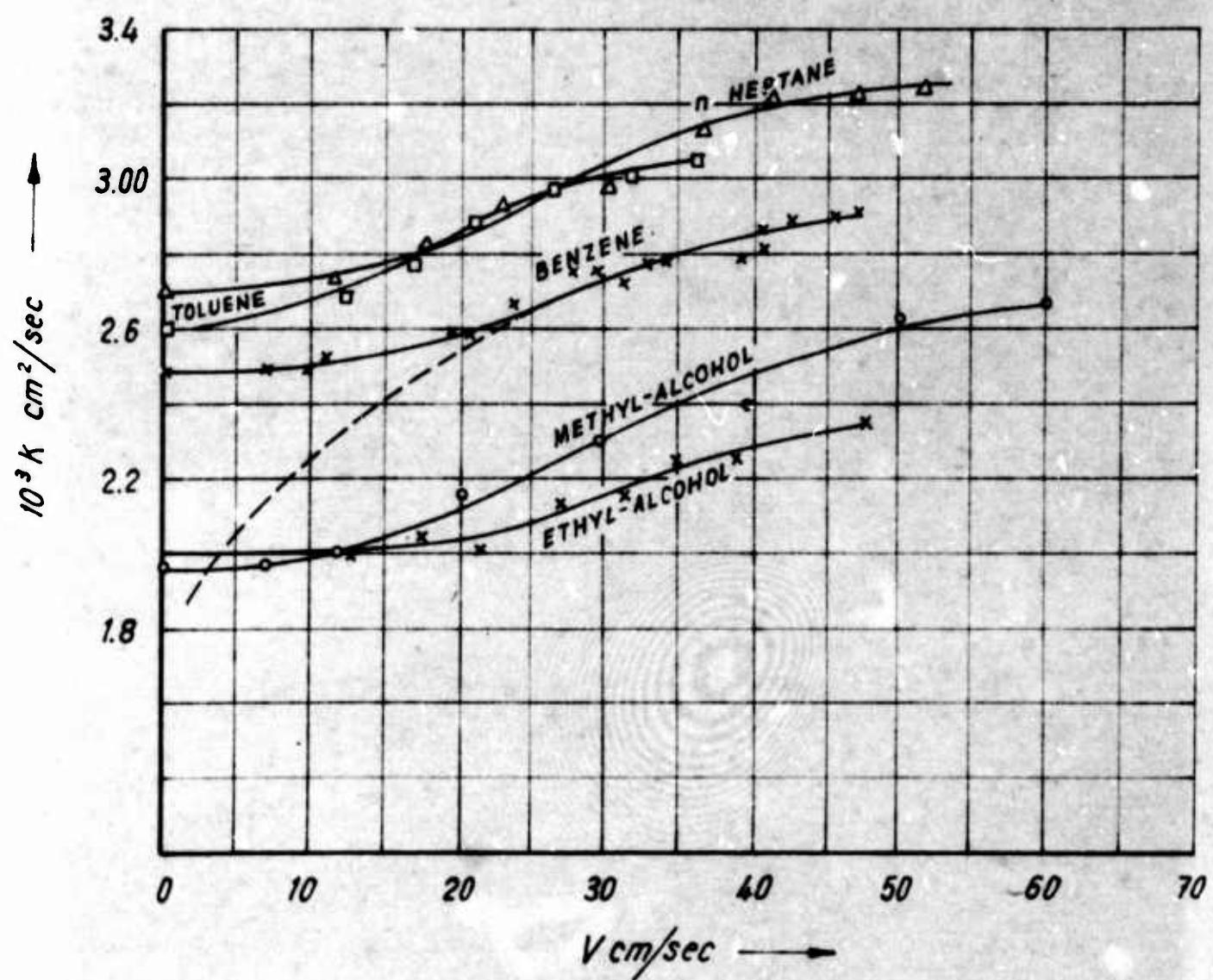
Fig. No 7 - Evaporation constants versus blowing velocity (T≈20°C)

BENZENE

FORCED CONVECTION
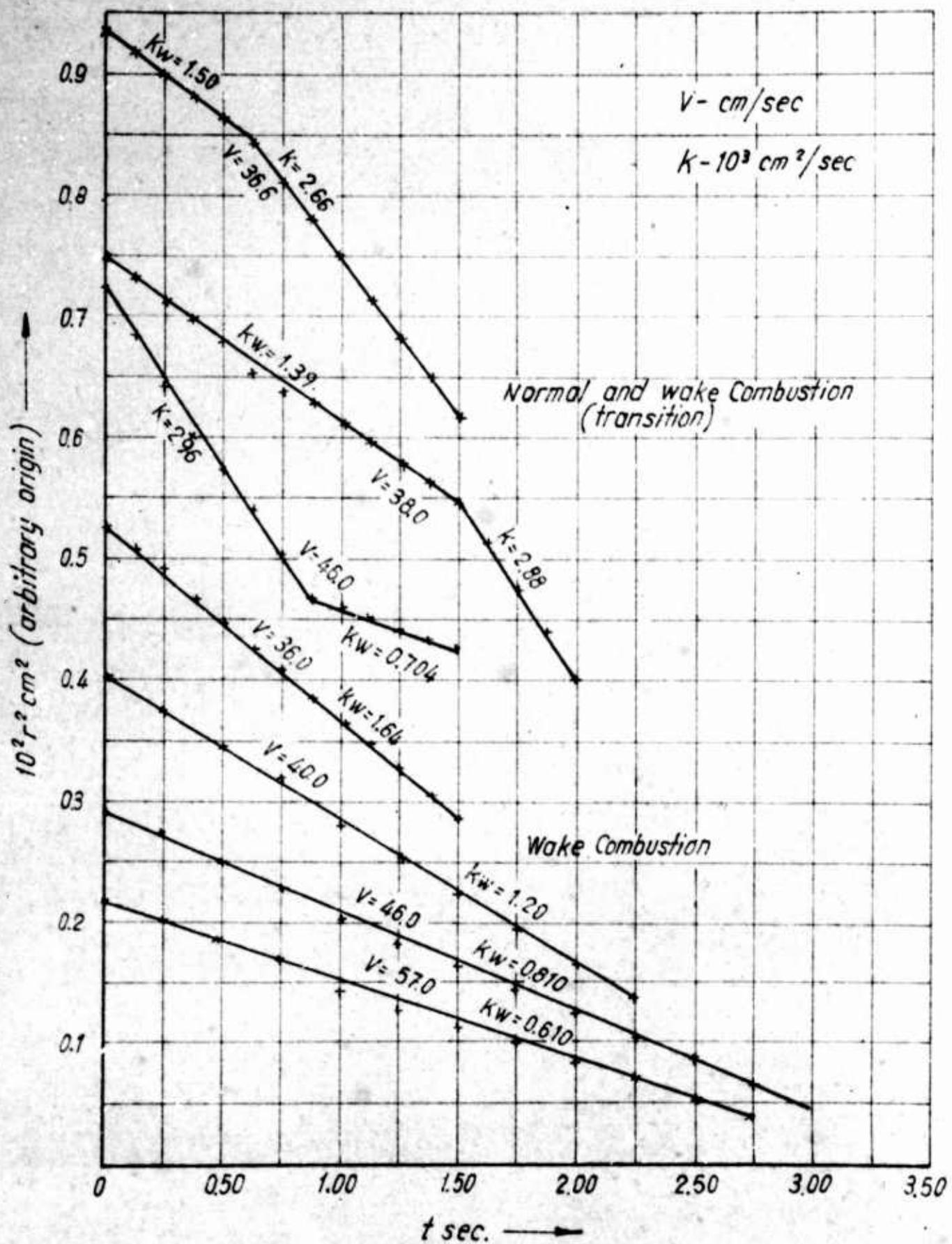
$(T \approx 20°C)$

Fig. No. 8 - Square radius versus time for normal and wake combustion.

TOLUENE
FORCED CONVECTION
### $(T \approx 20°C)$
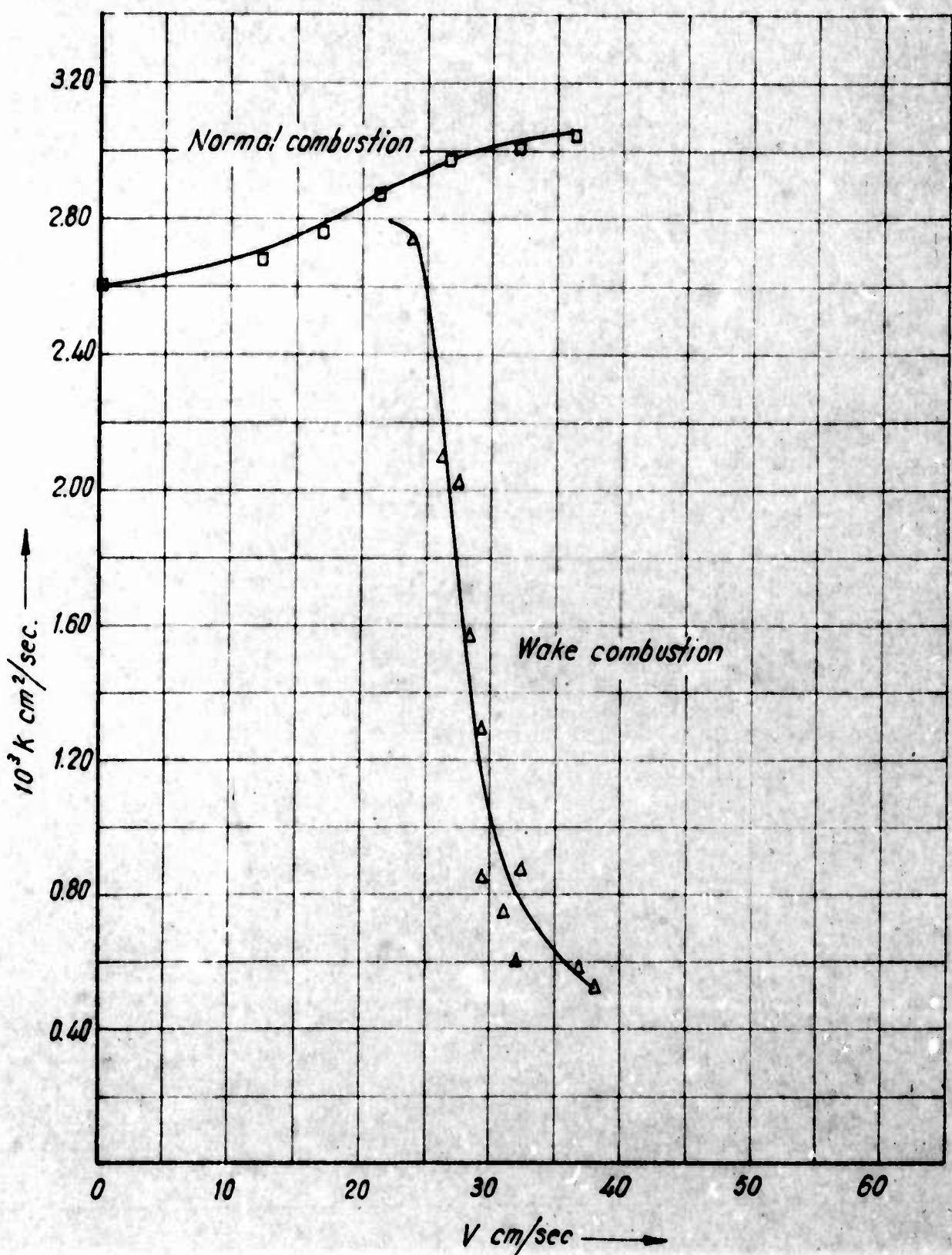
Fig. No 9 - Evaporation constants in normal
and wake combustion as a function
of blowing velocity.
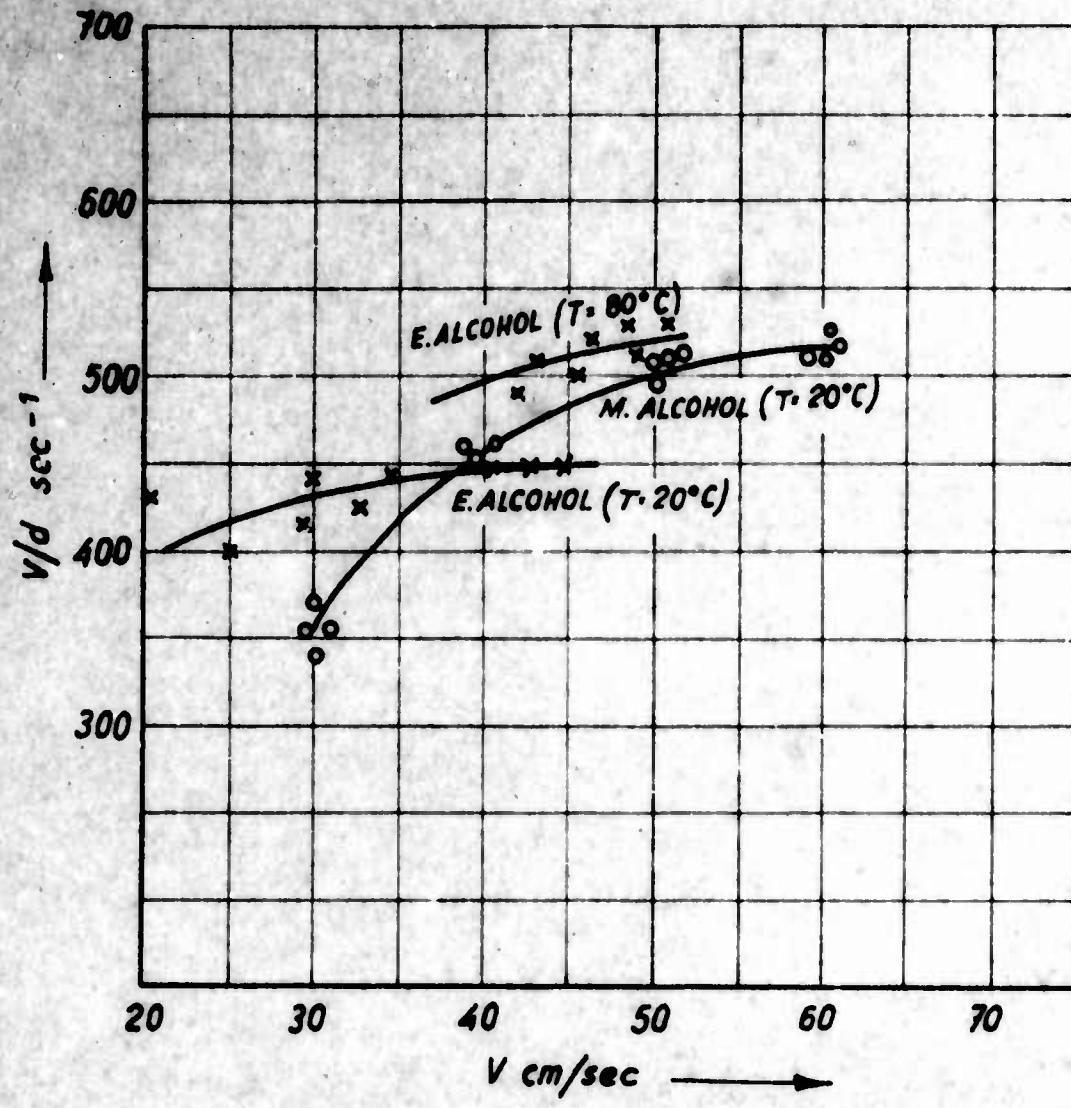
Fig. No 10 - Ratio: velocity/drop diameter for extinction versus blowing velocity.

BENZENE

INTERACTION EFFECTS
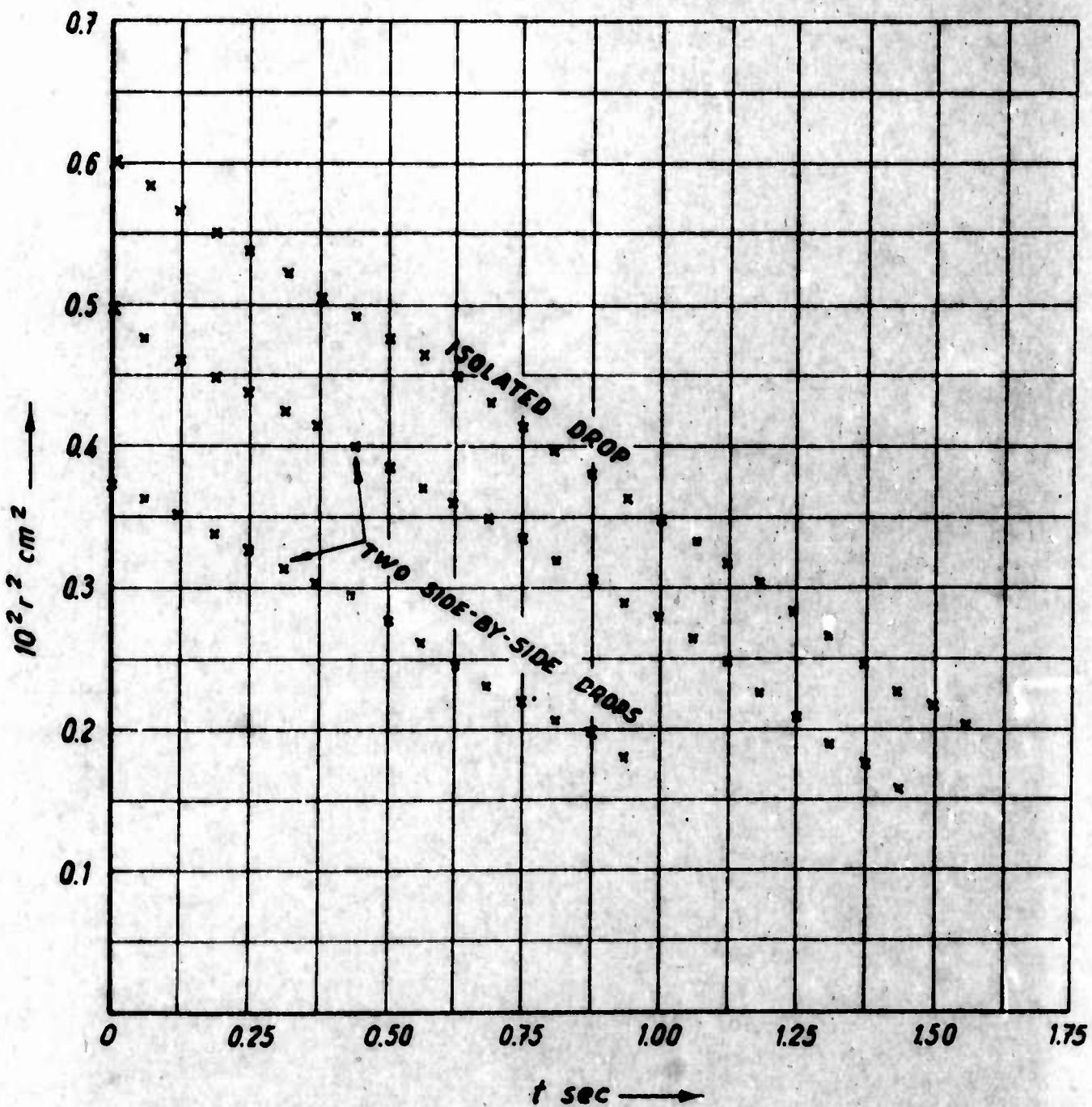
(T ≈ 20°C)

Fig. No 11 - Square radius versus time for an isolated drop and for two side-by-side drops.

BENZENE
INTERACTION EFFECTS
(T ≈ 20°C)
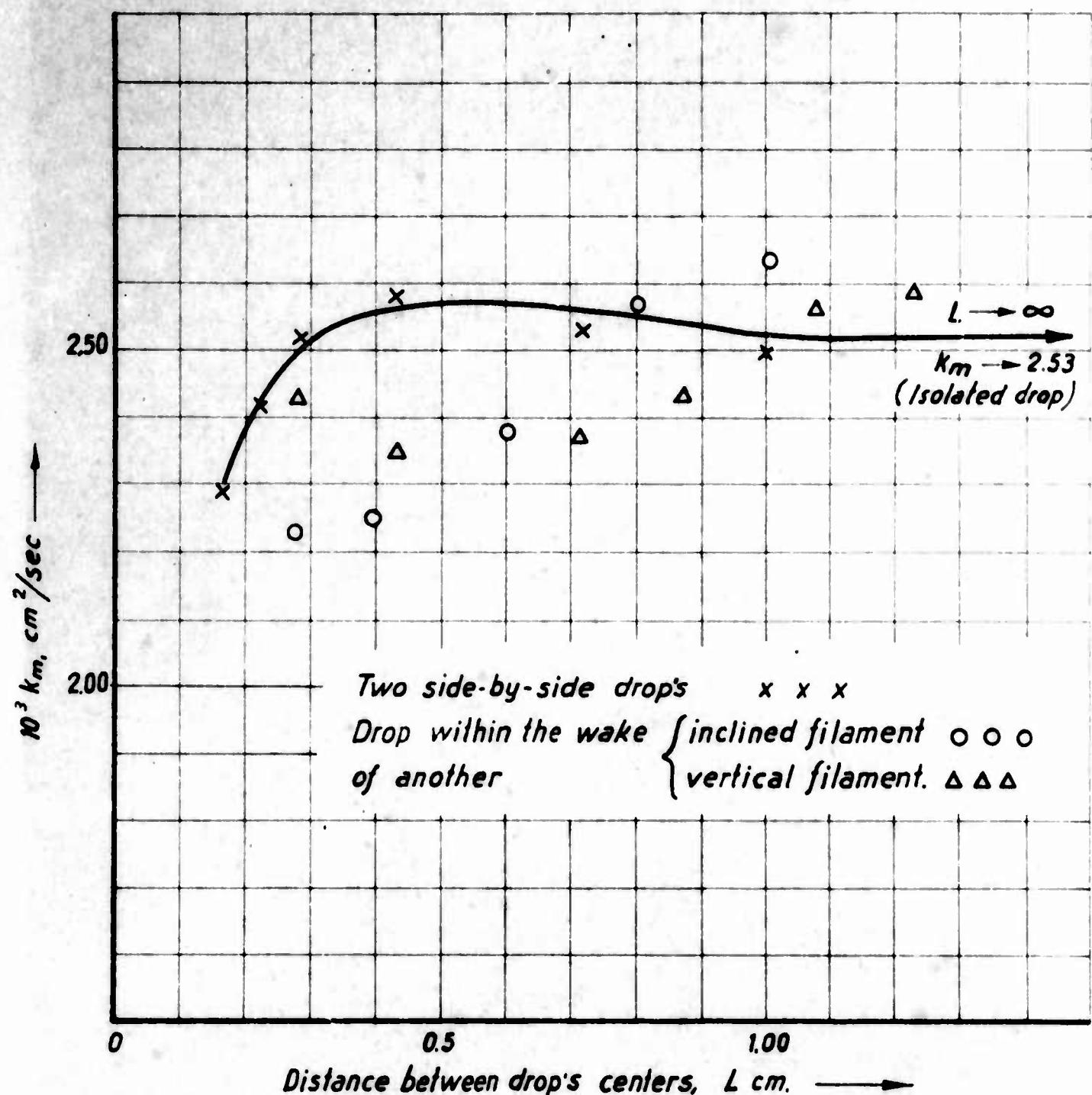
Fig. No 12 - Average evaporation constants as a function of distance between drop's centers.